

OPTIMAL GROUNDWATER RESOURCES MANAGEMENT OF AN OVEREXPLOITED AQUIFER UNDER GLOBAL CHANGE

Pantelis SIDIROPOULOS¹, Nikitas MYLOPOULOS¹ & Athanasios LOUKAS¹

(1) Department of Civil Engineering, University of Thessaly, Greece, email: psidirop@civ.uth.gr

ABSTRACT

This paper presents a study for finding the optimal management of an overexploited aquifer under global change. The study area is the aquifer of Lake Karla basin, located on the eastern part of Thessaly in Greece. An optimization method has been used to evaluate the optimum volume of water that can be extracted from the aquifer as well as the optimum position of the wells. The objective is the rise of the water table to a desirable sustainable level, taking into consideration the impacts of climate change. The modeling system consists of a series of interlinked models: a hydrological model, a lake-aquifer model, a reservoir operation model and a groundwater model. An optimization tool is used for the optimization exercise. The results of this study show that climate change plays an important role, as it affects the optimum volume of the extracted water and the position of the remaining irrigation wells.

1 INTRODUCTION

The watershed of Lake Karla, located in eastern Thessaly, is an intensely cultivated agricultural region. The intense and extensive agriculture of water demanding crops such as cotton, has resulted in the increase of groundwater pumping, both pumping rate and uncontrolled number of wells, which in turn has led to a dramatic drawdown of the water table. The aquifer of Lake Karla's basin is an example of the over-exploitation of groundwater resources.

Lake Karla occupied most of the eastern part of the plain. It was one of the most important Greek wetlands and a natural reservoir, which provided water storage and recharge to the groundwater system. However, technical studies recommended draining the lake and building a smaller reservoir instead of the natural lake for flood protection and for the revelation of agricultural fields. Although the lake was drained in 1962, the suggested reservoir was never built. This delay has created a series of environmental problems, such as the limitation of the natural recharge of the underlying aquifer and the increase of groundwater pumping among others, which in turn have caused a dramatic drawdown of the water table. Today, the head losses at the zones with the most intense pumping have reached up to 80 m during the last 20 years. The suggested plan for the restoration of Lake Karla began a few years ago and suggests the creation of a 38 km² reservoir in the lowest part of the old lakebed, through the construction of two embankments, one in the eastern part and one in the western part of the lake. This

partial restoration is expected to reverse the drawdown of the water table and other adverse environmental problems caused by the lake drainage.

The goal of this study is to propose a management tool, under global change, for the optimal use of groundwater resources, after lake's Karla restoration,. This management tool takes into account the timetable of the reservoir, which will provide water for irrigation needs to the surrounding cultivations, as well as the shutdown of the irrigation wells.

2 STUDY AREA

The natural basin of Karla covered an area of 1,663 km² but after the construction of complimentary works, the drainage area of the restored lake Karla has been 1171 km² (Fig. 1). The climate at the eastern part of Thessaly is typical Mediterranean. The average temperature is 16-17° C and the mean annual relative humidity is 67%-72%. The average precipitation is 500 – 700 mm. Generally, rainfall is rare from June to August.

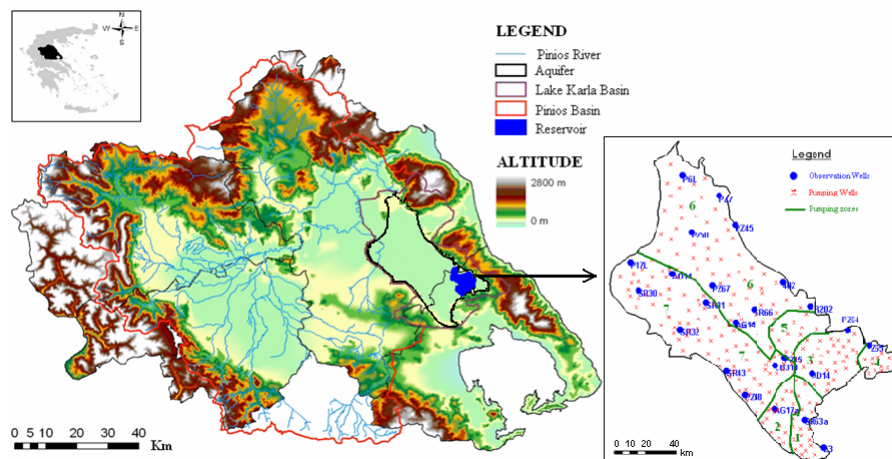


Figure 1. Map of Thessaly indicating Karla Lake basin, its underlying aquifer and its reservoir.

The geological structure consists mainly of grains of various sizes. The plain consists of aquiferous, essentially sandy intercalations separated by layers of clay to silty-clay and Neogene deposits consisting of marls and conglomerates and is bound by schists and karstic limestones or marbles. Impermeable geological structures cover a 30.6% of the total area, karstic aquifers cover a 14.5% and permeable structures, which appear mainly in the plain, cover a 54.9%. The underlying aquifer is located in the lower part of basin covering an area of 500 km². Most of the aquifer area is plain with an altitude ranging from 45 to 65 m. Only to the southwest the altitude reaches up to 90 m. To the east there is the Mavrovouni Mountain which consists of impermeable bedrocks as schist. The Thessally plain continues to the west with the the Halkodonion Mountain located to the southwest. The basement rocks consist of impermeable marbles and schist as presented by Costandinidis (1978).

3 METHODOLOGY

An optimization method has been used to evaluate the optimum volume of water that can be extracted from the aquifer as well as the optimum position of the remaining wells with the objective of the water table rise to a desirable sustainable level. The method has been applied taking into consideration climate change. The modeling system consists of a series of interlinked models: a hydrological model (UTHBAL), a lake-aquifer model (LAK3), a reservoir operation model (UTHRL) a groundwater model (MODFLOW). The modeling system has been calibrated for the historical period against observed runoff and groundwater hydraulic heads. An optimization tool (GWM) is used for the optimization exercise. The climate change forcing on precipitation and temperature has been evaluated using the output of the Canadian Centre for Climate Model Analysis General Circulation Model (CGCMa2) and a hybrid downscaling method as shown by Vasiliades et al. (2009) which combines a multiple regression (MLR) model and a timeseries model. The climate change has been assessed for the SRESA2 and SRESB2 socioeconomic emissions scenarios.

3.1 Hydrological Model

A monthly conceptual hydrological model (UTHBAL) has been used (Loukas et al., 2007) for the assessment of the surface runoff. The water balance model uses as input the time series of the mean areal precipitation, the mean areal temperature and the mean areal potential evapotranspiration. The model divides the total precipitation into rainfall and snowfall, since this is essential for accurate runoff simulation for snow-covered mountain watersheds. The water balance model uses a soil moisture mechanism to allocate the watershed runoff into three components namely, the surface runoff, the medium runoff and the baseflow runoff. Its output is the actual evapotranspiration, the surface runoff, the soil moisture, and the groundwater recharge, which is the data linking to the groundwater model. The UTHBAL model was calibrated using the observed monthly values of Lake Karla's basin runoff to Pagasitikos Gulf for the period October 1960 to September 2002 and was used to produce synthetic time series of runoff and groundwater recharge data for the Lake Karla watershed for the period October 2012 to September 2044 for the socioeconomic emissions scenarios SRESA2 and SRESB2.

3.2 Reservoir Operation Model

The operation of the reservoir was simulated considering the natural runoff inflows from its watershed area, any water transfers from nearby water resources, the water withdrawals as well as the net water losses. The natural surface runoff has been simulated as presented by the hydrological model and the net water losses of the reservoir were calculated as the subtraction of precipitation from evaporation from the reservoir water surface and the percolation losses. The model used for the simulation of the operation of reservoirs is a simple model as shown by Loukas et al. (2007). The reservoir operation model (UTHRL) calculates the spillway overflows and reservoir water storage. The calculated water stages of the reservoir were used for the calibration of the lake-aquifer interaction (LAK3) model.

3.3 Lake-Aquifer Model

The reservoir at Lake Karla was represented as an internal lake using the Lake Package (LAK3) of GMS as shown by Merritt and Konikow (2000). The lake-aquifer interaction was simulated in transient flow conditions, by updating at the end of each time step a water budget for the lake that is independent of the groundwater budget represented by the solution for heads in the aquifer. Implicit in the calculations of a lake water budget is the recomputation of current values of lake volume and stage. The lake stage is crucial in estimating ground-water seepage to and from the lake.

3.4 Groundwater Model

The phreatic aquifer of former Lake Karla, of about 500 km², has been simulated by a numerical model, using the MODFLOW code (Harbaugh and McDonald, 2000), discretized into an orthogonal grid of 40.000 cells, with a grid spacing of 200 m x 200 m and as a one layer aquifer (Sidiropoulos, 2004). There is a week hydraulic contact with the adjacent aquifer to the west, while the eastern boundary is a no flow boundary because of the presence of a schist layer. The impermeable bottom varies and consists of non rusty marbles and schists. Groundwater recharge data is obtained by the UTHBAL model. In order to estimate the water demand for irrigation, data regarding irrigated agricultural areas per crop and municipality were provided by the Greek Ministry of Agriculture. Based on these data, the study area was divided into 7 irrigation zones as shown in Figure 1 and Table I, according to the agricultural activity in the basin. The simulations were conducted for the period 1987 – 2044. The management period for which the simulation will be run is 2012-2044, since the reservoir is supposed to start operating in 2012. The extracted groundwater volume will be calculated from the optimization model. Data from 24 observation wells were used both for the initial head distribution (01/01/1987) as well as for the model calibration on the 01/01/1997. Hydraulic conductivity was the parameter for which MODFLOW was calibrated and was the only hydrogeologic parameter that was spatially distributed whilst the others had the same value over the area. Simple Kriging was used for spatial distribution of hydraulic conductivity (Mylopoulos and Sidiropoulos, 2009).

TABLE I. The irrigation zones of the study area and their annual water extraction in hm³.

Zones		1	2	3	4	5	6	7
Annual extracted groundwater volume for the period 1987-2012 (hm ³)	Irrigation	22.0	3.6	5.9	3.3	2.2	38.5	55.7
	Water supply	2.4	0	0	0.2	0.3	0	0
	Sum	22.4	3.6	5.9	3.5	1.5	38.5	55.7

The groundwater model is the core of the modeling system as it is the one that simulates the aquifer. Its outputs are maps with hydraulic heads and volumetric budgets of the aquifer. These outputs are finally used for the comparison of the scenarios SRESA2 and SRESB2.

3.5 Optimization Tool

The GWM model was used for the aquifer optimization. GWM is a Ground-Water Management Process for the U.S. Geological Survey modular three-dimensional ground-water model, MODFLOW-2000, as shown by Ahfeld et al. (2005). GWM uses a response-matrix approach to solve several types of linear, nonlinear, and mixed-binary linear ground-water management formulations. Each management formulation consists of a set of decision variables, an objective function, and a set of constraints. The Response Matrix Solution (RMS) Package of GWM uses the Ground-Water Flow Process of MODFLOW to calculate the change in head at each constraint location that results from a perturbation of a flow-rate variable. These changes are used to calculate the response coefficients.

The formulation of the management problem is presented by the following equations:

$$\text{Maximize} \sum_{t=1}^T \sum_{n=1}^N Q_n^t \quad (1)$$

subject to:

$$h_i^{2044} \geq h_i^{1987}, i = 1, \dots, n \quad (2)$$

$$Q_n \geq 0 \text{ m}^3 / \text{s}, n = 1, \dots, N \quad (3)$$

where Q_n is the withdrawal flow rate of the managed wells in m^3/s , N is the total number of managed wells, T is the number of stress periods for the management period 2012-2044, h_i is the hydraulic head constraint where the exponent refers to the year. So the target of the optimization problem is to find the maximum allowable extraction volume for the period 2012-2044, in order for the hydraulic heads at the managed wells at the end of the management period to be equal or higher than the ones of year 1987, as shown in figure 2a. This year was selected as it is considered to be the start of the over-exploitation of the aquifer.

The optimization problem is in nonlinear formulation and is solved by the sequential linear programming (SLP) algorithm which is referred to as the SLP approach. It is based on repeated linearization of the nonlinear features in the management problem, and is implemented by recalculating the response matrix for each sequential linear program. Each one of these linear programs is solved using a simplex method. As mentioned before the optimization exercise is finally solved for two socioeconomic emissions scenarios SRESA2 and SRESB2, which will determine the number and position of managed wells and the optimum extracted groundwater volume.

4 RESULTS

The model was run for the historical period 1987-2012, using the data presented before, without reservoir operation. The output is a hydraulic head map, as shown in figure 3, and the volumetric budget of the aquifer. Regarding the last, the renewable water which is from recharge and side inflows is 932.47 hm^3 and the extracted one is

2113.6 hm³ for this period. So the 1181.13 hm³ or 73.82 hm³/y were extracted from the non renewable resources of the aquifer, fact that has led to its over-exploitation. This becomes clear when comparing figures 2 and 3. The hydraulic head difference reaches up to 80 m in the vicinity of irrigation wells.

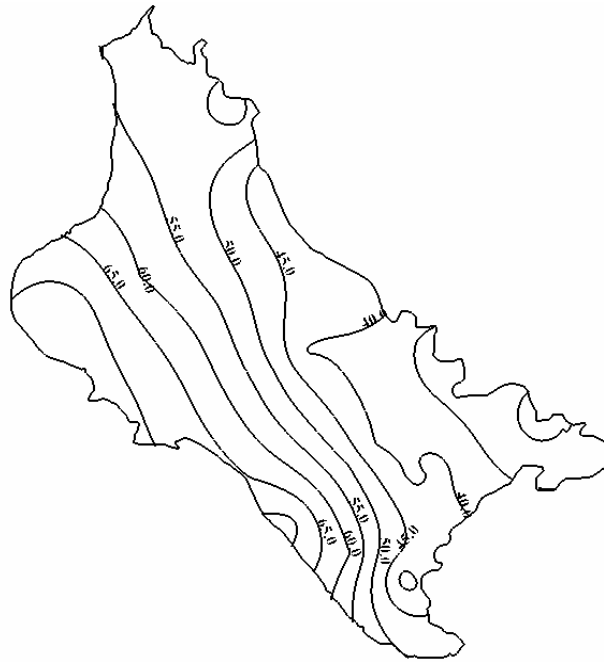


Figure 2. Hydraulic heads counters of aquifer for year 1987

For the management period 2012-2044, the inflows to the aquifer change according to the socioeconomic emissions scenarios SRESA2 and SRESB2, as each one creates different time series of precipitation and temperature. This results in differences mainly in recharge volumes, as the lake seepage and side inflows are only slightly changed. These scenarios, which were generated from Intergovernmental Panel on Climate Change (IPCC, 2001), are:

SRESA2: assumes a strong, but regionally oriented economic growth and fragmented technological change with an emphasis on human wealth. It represents a high emission scenario.

SRESB2: emphasizes on the protection of the environment and the social equity, but also relies on local solutions for economic, social, and environmental sustainability and represents a low emission scenario.



Figure 3. Hydraulic heads counters of aquifer for year 2012.

The model was run again for the same management period for both scenarios, as the optimization tool requires a solution of the system before it starts the optimization process. The SRESB2 scenario enriches the aquifer with higher values of recharge than the SRESA2 scenario. The SRESB2 produces 1629.56 hm^3 or $49.381 \text{ hm}^3/\text{y}$ renewable water resources while the SRESA2 produces 1214.47 hm^3 or $36.802 \text{ hm}^3/\text{y}$. But, at this simulation run no irrigation wells were operated in order to find in which areas of the aquifer the hydraulic head was higher than the one of 1987. These areas allow us to extract the renewable groundwater using as managed wells the existing irrigation wells. So, these areas come from the hydraulic head difference maps for the years 2044 and 1987 for the two scenarios as shown in Figure 4. The continuous line refers to the zero hydraulic head contour of SRESA2 and the dashed one to SRESB2 respectively. Water can be extracted only from the eastern areas, mainly irrigation zones 3,4 and 6. The SRESB2 contour offers a bigger area of aquifer for water extraction than the one of SRESA2 because the first one produces greater volumes of renewable water. The proposed managed wells of scenario SRESB2 are 98 of a total of 238 of the aquifer and for scenario SRESA2 they are 68.

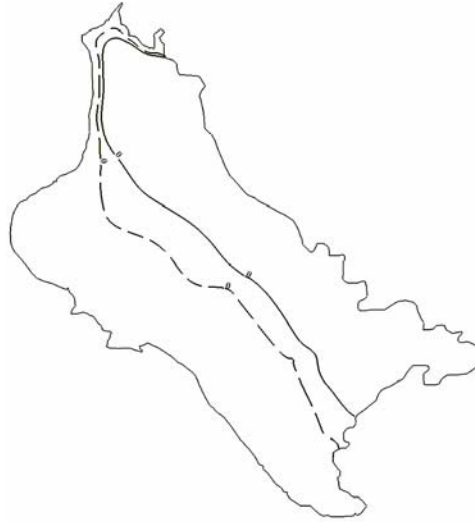


Figure 4. Contours of zero hydraulic head differences of years 2044 and 1987 for SRESA2 scenario (continuous line) and SRESB2 (dashed line).

The optimization process was initiated using equations 1-3 for both scenarios. In scenario SRESA2 only 35 of the 68 proposed managed irrigation wells were used and in scenario SRESB2 only 42 of 98. The optimum groundwater for SRESB2 is 307.628 hm^3 for the period 2012-2044 or $9.6134 \text{ hm}^3/\text{y}$, greater than the one of SRESA2 which is 152.266 hm^3 for period 2012-2044 or $4.758 \text{ hm}^3/\text{y}$. It is obvious that in the case of the SRESB2 scenario from the annual 49.381 hm^3 of renewable water, only 9.6134 hm^3 were extracted and in the case of the SRESA2 scenario from the annual 36.802 hm^3 renewable water, only 4.758 hm^3 were extracted. The remaining renewable water was used for the restoration of the water table in order for the hydraulic head in 2044 to be equal with the one in 1987. These results are presented in Figures 5 and 6.

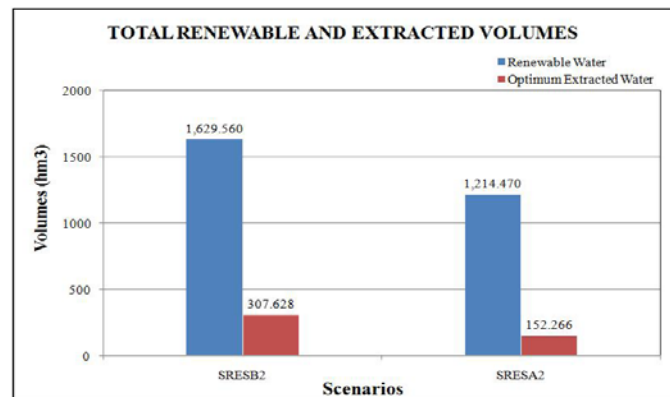


Figure 5. Total renewable and optimum extracted water of aquifer for scenarios SRESA2 and SRESB2 for the entire management period.

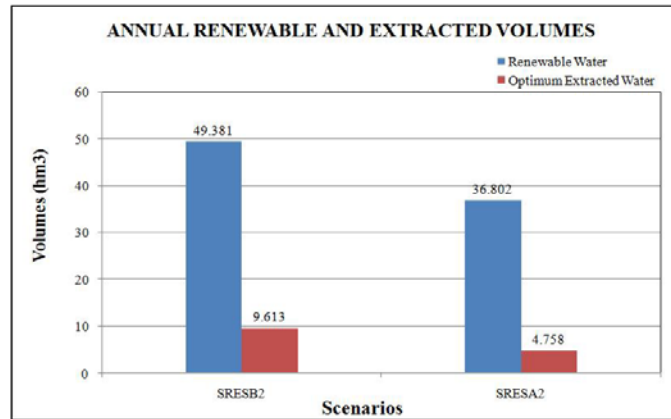


Figure 6. Annual renewable and optimum extracted water of the aquifer for scenarios SRESA2 and SRESB2 for the entire management period.

Finally the proposed optimum extracted groundwater for period 2012-2044 is presented in Table II for both scenarios for each irrigation zone.

TABLE II. The irrigation zones of the study area and their annual water extraction in hm^3 .

Zones		1	2	3	4	5	6	7
Annual extracted groundwater volume for the period 2012-2044 (hm^3) SRESA2	Irrigation	0	0	0.5971	1.3268	0	2.8341	0
Annual extracted groundwater volume for the period 2012-2044 (hm^3) SRESB2	Irrigation	0	0	1.9187	1.9312	0	5.7631	0

5 CONCLUSIONS

A simulation optimization method has been used to evaluate the optimum volume of water that can be extracted from the aquifer and the optimum position of the remaining wells with the objective being a water table rise to a desirable sustainable level. The case study is the aquifer of former Lake Karla which has been in an over-exploitation state during the last decades. As a new reservoir has been constructed and is going to operate in 2012 this study proposes the optimal management of the aquifer, under the climate change impact. The optimization exercise has been tested for two scenarios, SRESA2 and SRESB2.

The results show that the impact of climate change is important on the optimal groundwater resources management, as it determines the optimum volume of the extracted water and the number and the position of the remaining irrigation wells. The difference of the renewable water between the two scenarios is able to lead to two different optimization problems in the same aquifer, as the areas in which the groundwater is allowable for extraction differ. The study and the forecasting of climate plays an important role in the management of water resources regardless of how

accurate a management tool is. If the forecasting has a high degree of uncertainty, the management tool will be proven useless.

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